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AUTHOR(S):

Heck, Horst; Kim, Hyunseok; KOZONO, Hideo

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Leray's problem on D -solutions to the stationary Navier-Stokes equations past an obstacle

Horst Heck

Department of Engineering and Information Technology
Bern University of Applied Sciences
CH-3400 Burgdorf, Switzerland
horst.heck@bfh.ch

Hyunseok Kim

Department of Mathematics
Sogang University
Seoul, 121-742, Korea
kimh@sogang.ac.kr

Hideo KOZONO

Department of Mathematics
Waseda University
Tokyo 169-8555, Japan
kozono@waseda.jp

Introduction.

Let Ω be an exterior domain in \mathbb{R}^3 with smooth boundary $\partial\Omega \in C^\infty$. We consider the stationary Navier-Stokes equations in Ω :

$$(N-S) \quad \begin{cases} -\Delta u + u \cdot \nabla u + \nabla p = f & \text{in } \Omega, \\ \operatorname{div} u = 0 & \text{in } \Omega, \\ u = 0 & \text{on } \partial\Omega, \\ u(x) \rightarrow u^\infty & \text{as } |x| \rightarrow \infty, \end{cases}$$

where $u = u(x) = (u_1(x), u_2(x), u_3(x))$ and $p = p(x)$ denote the unknown velocity vector and the unknown pressure at $x = (x_1, x_2, x_3) \in \Omega$, while $f = f(x) = (f_1(x), f_2(x), f_3(x))$ is the given external force, and $u^\infty = (u_1^\infty, u_2^\infty, u_3^\infty)$ is the prescribed constant vector in \mathbb{R}^3 at infinity. In the pioneer work of Leray [14], it was shown that for every $f \in \dot{H}^{-1,2}(\Omega) \equiv \dot{H}_0^{1,2}(\Omega)^*$ and for every $u^\infty \in \mathbb{R}^3$, there exists at least one weak solution u of (N-S) with $\int_\Omega |\nabla u(x)|^2 dx < \infty$ such that

$$\int_\Omega |u(x) - u^\infty|^6 dx < \infty.$$

Here and in what follows, $\dot{H}_0^{1,q}(\Omega)$ denotes the closure of $C_0^\infty(\Omega)$ with respect to the homogeneous norm $\|\nabla u\|_{L^q}$ for $1 < q < \infty$. Leray named such a weak solution u D -solution of (N-S) because it has a finite Dirichlet integral in Ω . The asymptotic behavior of D -solution u at infinity had been improved by Finn [3], Fujita [4] and Ladyzhenskaya [13] in such a way that

$$u(x) \rightarrow u^\infty \quad \text{uniformly as } |x| \rightarrow \infty,$$

provided f has a compact support in Ω . In his paper [14], Leray proposed the problem whether every D -solution u satisfies the energy identity

$$(EI) \quad \int_{\Omega} \nabla u \cdot \nabla(u - a) dx + \int_{\Omega} u \cdot \nabla a \cdot (u - a) dx = \langle f, u - a \rangle$$

for all $a \in C^1(\bar{\Omega})$ such that $\operatorname{div} a = 0$ in Ω , $a|_{\partial\Omega} = 0$, $a(x) \equiv u^\infty$ for all $x \in \Omega$ satisfying $|x| \geq R$ with some large $R > 0$. Here $\langle \cdot, \cdot \rangle$ denotes the duality pairing of $\dot{H}^{-1,2}(\Omega)$ and $\dot{H}_0^{1,2}(\Omega)$. The second important question is a uniqueness problem of D -solutions. It is still an open question whether there exists a small constant δ such that if $\|f\|_{\dot{H}^{1,2}} + |u^\infty| \leq \delta$, then the D -solution u of (N-S) is unique. This is so-called a uniqueness theorem of D -solutions for arbitrary small given data $f \in \dot{H}^{-1,2}(\Omega)$ and $u^\infty \in \mathbb{R}^3$.

In this article, we shall give final affirmative answers to these two questions provided $u^\infty \neq 0$. It should be noted that the corresponding results to those in the case $u^\infty = 0$ are still open questions. See e.g., Nakatsuka [15]. There is another notion of physically reasonable (PR) solutions introduced by Finn [2], [3]. We call the solution u of (N-S) physically reasonable if it holds

$$(PR) \quad u(x) - u^\infty = O(|x|^{-\alpha}) \quad \text{as } |x| \rightarrow \infty$$

for some $\alpha > 1/2$. If u is a PR-solution of (N-S) with $f \in C_0^\infty(\Omega)$, then u behaves like

$$(WR) \quad u(x) - u^\infty = O(|x|^{-1}(1 + s_x)^{-1}), \quad s_x \equiv |x| - \frac{x \cdot u^\infty}{|u^\infty|} \quad \text{as } |x| \rightarrow \infty,$$

which exhibits a parabolic wake region behind the obstacle. It had been shown by Finn [3] that in the case when $f \in C_0^\infty(\Omega)$, every PR-solution u becomes necessarily a D -solution. The converse assertion was treated by Babenko [1] who proved that if $f \equiv 0$, then every D -solution u of (N-S) satisfies (PR) with $\alpha = 1$. As a result, it turns out that every D -solution with $f \equiv 0$ has a parabolic wake region such as (WR). Later on, Galdi [6], [7], [8], [9] and Farwig [5] succeeded to handle more general f by introducing anisotropic weight functions, and obtained more precise asymptotic behavior of u than (WR) in the class of PR-solutions. Furthermore, Kobayashi-Shibata [11] showed the stability of PR-solutions for small f and u^∞ in terms of the Oseen semi-group in L^p -spaces.

1 Results.

Before stating our results, let us introduce some notation and then give our definition of D -solutions of (N-S). $C_{0,\sigma}^\infty(\Omega)$ is the set of all C^∞ -vector functions $\varphi = (\varphi_1, \varphi_2, \varphi_3)$ with compact support in Ω , such that $\operatorname{div} \varphi = 0$. For $1 < q < \infty$, $L^q(\Omega)$ stands for all L^q -summable vector functions on Ω with the norm $\|\cdot\|_{L^q}$. We denote by (\cdot, \cdot) the duality pairing between $L^q(\Omega)$ and $L^{q'}(\Omega)$, where $1/q + 1/q' = 1$. $\dot{H}_0^{1,q}(\Omega)$ denotes the closure of $C_{0,\sigma}^\infty(\Omega)$ with respect to the homogeneous norm $\|\nabla \varphi\|_{L^q}$, where $\nabla \varphi = \left(\frac{\partial \varphi_i}{\partial x_j} \right)$, $i, j = 1, 2, 3$. $\dot{H}^{-1,q}(\Omega)$ is the dual space of $\dot{H}_0^{1,q'}(\Omega)$, and $\langle f, \phi \rangle$ denotes the duality pairing between $f \in \dot{H}^{-1,q}(\Omega)$ and $\phi \in \dot{H}_0^{1,q'}(\Omega)$. Finally, for $u^\infty \in \mathbb{R}^3$, we define the space $A(u^\infty)$ by

$$A(u^\infty) \equiv \{a \in C^1(\bar{\Omega}); \operatorname{div} a = 0, a|_{\partial\Omega} = 0, a(x) \equiv u^\infty \quad \text{for all } x \in \mathbb{R}^3 \text{ satisfying } |x| > R\}$$

with some $R > 0$.

Our definition of D -solutions to (N-S) reads as follows.

Definition. Let $f \in \dot{H}^{-1,2}(\Omega)$ and $u^\infty \in \mathbb{R}^3$. A measurable function u on Ω is called a D -solution of (N-S) if the following conditions (i), (ii) and (iii) are satisfied.

- (i) $\nabla u \in L^2(\Omega)$ with $\operatorname{div} u = 0$ in Ω and $u = 0$ on $\partial\Omega$;
- (ii) $u(\cdot) - u^\infty \in L^6(\Omega)$;
- (iii) it holds that

$$(E) \quad (\nabla u, \nabla \varphi) + (u \cdot \nabla u, \varphi) = \langle f, \varphi \rangle \quad \text{for all } \varphi \in C_{0,\sigma}^\infty(\Omega).$$

Remark. For every D -solution u of (N-S), there exists a unique scalar function $p \in L_{loc}^2(\Omega)$ up to an additive constant such that

$$(E') \quad (\nabla u, \nabla \phi) + (u \cdot \nabla u, \phi) + (p, \operatorname{div} \phi) = \langle f, \phi \rangle \quad \text{for all } \phi \in C_0^\infty(\Omega).$$

Our first result on the energy identity (EI) now reads:

Theorem 1.1 Assume that $f \in \dot{H}^{-1,2}(\Omega)$ and $u^\infty \in \mathbb{R}^3$ with $u^\infty \neq 0$. Then every D -solution u of (N-S) satisfies

$$(1.1) \quad (\nabla u, \nabla u) - (\nabla u, \nabla a) + (u \cdot \nabla a, u - a) = \langle f, u - a \rangle \quad \text{for all } a \in A(u^\infty).$$

Moreover, if in addition $f \in \dot{H}^{-1,2}(\Omega) \cap L^q(\Omega)$ for some $1 < q < 2$, then it holds that

$$(1.2) \quad \int_{\Omega} |\nabla u|^2 dx + u^\infty \cdot \int_{\partial\Omega} T(u, p) \cdot \nu dS = \langle f, u - u^\infty \rangle,$$

where $T(u, p) \equiv \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \delta_{ij} p \right)_{1 \leq i, j \leq 3}$ denotes the stress tensor and where ν is the unit outer normal to $\partial\Omega$.

Remarks. (i) Galdi [8] and Farwig [5] showed a similar result to that of Theorem 1.1 under the assumption that $f \in \dot{H}^{-1,2}(\Omega) \cap L^{\frac{4}{3}}(\Omega) \cap L^{\frac{3}{2}}(\Omega)$. On the other hand, for the validity of the energy identity (1.1), we do not need any condition on f except for $f \in \dot{H}^{-1,2}(\Omega)$.

(ii) The corresponding problem for $u^\infty = 0$ is still open. Indeed, up to the present, the energy identity (1.1) is shown under the hypothesis that $u \in \dot{H}^{1,2}(\Omega) \cap L^{3,\infty}(\Omega)$, where $L^{q,r}(\Omega)$ denotes the Lorentz space on Ω . For instance, see Kozono-Yamazaki [12].

Next, we consider the uniqueness of D -solutions under the smallness assumption on the given data.

Theorem 1.2 There is a constant $\delta_1 = \delta_1(\Omega) > 0$ such that if $u^\infty \neq 0$ and $f \in \dot{H}^{-1,2}(\Omega)$ satisfy

$$(1.3) \quad \|f\|_{\dot{H}^{-1,2}} + |u^\infty| \leq \delta_1 |u^\infty|^{\frac{1}{2}},$$

then there exists a unique D -solution u of (N-S). Moreover, such a solution u is necessarily subject to the estimate

$$(1.4) \quad |u^\infty|^{\frac{1}{4}} \|u - u^\infty\|_{L^4} + \|\nabla u\|_{L^2} \leq C(\|f\|_{\dot{H}^{-1,2}} + |u^\infty|),$$

where $C = C(\Omega)$.

Remarks. (i) Galdi [8] showed that if $u^\infty \neq 0$ and $f \in L^{\frac{6}{5}}(\Omega) \cap L^{\frac{3}{2}}(\Omega)$ satisfy

$$\|f\|_{L^{\frac{6}{5}}} + |u^\infty| \leq \delta_1$$

then there exists a unique D -solution. Since $L^{\frac{6}{5}}(\Omega) \subset \dot{H}^{-1,2}(\Omega)$, our result covers that of Galdi [8]. Furthermore, we do not need any redundant assumption such as $f \in L^{\frac{3}{2}}(\Omega)$. Hence, Theorem 1.2 seems to be a final answer to Leray's question on uniqueness of D -solutions for small data.

(ii) The case when $u^\infty = 0$, such a uniqueness result as in Theorem 1.2 is known in more restrictive situations. For instance, Nakatsuka [15] treated the case $u^\infty = 0$, and proved that for every $3 < r < \infty$ there is a constant $\delta = \delta(r) > 0$ such that if $\{u, p\}$ and $\{v, q\}$ with $\nabla u, \nabla v, p, q \in L^{\frac{3}{2},\infty}(\Omega)$ satisfy (E') and if

$$\|u\|_{L^{3,\infty}} \leq \delta, \quad v \in L^3(\Omega) + L^r(\Omega),$$

then it holds that

$$\{u, p\} = \{v, q\}.$$

In his result, it is necessary to assume the smallness of one solution u and some redundant regularity on another solution v . It is still an open question whether any norm of solutions u of (N-S) with $u^\infty = 0$ can be controlled by f . For details, we refer to Kim-Kozono [10].

2 Oseen equations.

In this section, we investigate the following Oseen equations.

$$(Os) \quad \begin{cases} -\Delta v + u^\infty \cdot \nabla v + \nabla \pi = f & \text{in } \Omega, \\ \operatorname{div} v = 0 & \text{in } \Omega, \\ v = 0 & \text{on } \partial\Omega, \\ v(x) \rightarrow 0 & \text{as } |x| \rightarrow \infty. \end{cases}$$

Let us introduce the two function spaces $\tilde{H}^{1,q}(\Omega)$ and $\tilde{H}^{2,q}(\Omega)$ defined by

$$\begin{aligned} \tilde{H}^{1,q}(\Omega) &\equiv \{v \in L^{\frac{4q}{4-q}}(\Omega); \nabla v \in L^q(\Omega)\}, \quad 1 < q < 4, \\ \tilde{H}^{2,q}(\Omega) &\equiv \{v \in \tilde{H}^{1,\frac{4q}{4-q}}(\Omega); \nabla^2 v \in L^q(\Omega)\}, \quad 1 < q < 2. \end{aligned}$$

Then we have the following results on unique solvability of (Os).

Lemma 2.1 *Let $u^\infty \neq 0$. Assume that $1 < q_1, q_2 < 4$. The solution $\{v, \pi\} \in \tilde{H}^{1,q_1}(\Omega) + \tilde{H}^{1,q_2}(\Omega) \times L^1_{loc}(\Omega)$ of (Os) is unique.*

Lemma 2.2 (i) For $f \in \dot{H}^{-1,q}(\Omega)$ with $\frac{3}{2} < q < 4$, there exists a unique solution $\{v, \pi\} \in \tilde{H}^{1,q}(\Omega) \times L^q(\Omega)$ of (Os). Moreover, for every $\frac{3}{2} < q < 3$ and every $M > 0$ there is a constant $C = C(q, M, \Omega)$ such that if $\{v, \pi\} \in \tilde{H}^{1,q}(\Omega) \times L^q(\Omega)$ is a solution of (Os) with $|u^\infty| \leq M$, then it holds that

$$k_1 \|v\|_{L^{\frac{4q}{4-q}}} + \|\nabla v\|_{L^q} + \|\pi\|_{L^q} \leq C \|f\|_{\dot{H}^{-1,q}},$$

where $k_1 \equiv \min.\{1, |u^\infty|^{\frac{1}{4}}\}$.

(ii) For every $f \in L^q(\Omega)$ with $1 < q < 2$, there exists a unique solution $\{v, \pi\} \in \tilde{H}^{2,q}(\Omega) \times L^{q*}(\Omega)$ of (Os) with $\nabla \pi \in L^q(\Omega)$, where $\frac{1}{q*} = \frac{1}{q} - \frac{1}{3}$. Moreover, for every $1 < q < \frac{3}{2}$ and every $M > 0$ there is a constant $C = C(q, M, \Omega)$ such that if $\{v, \pi\} \in \tilde{H}^{1,q}(\Omega) \times L^q(\Omega)$ is a solution of (Os) with $|u^\infty| \leq M$, then it holds that

$$k_2 \|v\|_{L^{\frac{2q}{2-q}}} + k_1 \|\nabla v\|_{L^{\frac{4q}{4-q}}} + \|\nabla^2 v\|_{L^q} + \|\pi\|_{L^{q*}} + \|\pi\|_{L^q} \leq C \|f\|_{L^q},$$

where $k_2 = k_1^2 \equiv \min.\{1, |u^\infty|^{\frac{1}{2}}\}$.

3 Proof of Theorems.

The following lemma is based on Lemma 2.2 and plays a key role for the proof of Theorem 1.1.

Lemma 3.1 Let $u^\infty \neq 0$ and $f \in \dot{H}^{-1,2}(\Omega)$. Let u be a D -solution of (N-S).

(i) If in addition $f \in \dot{H}^{-1,2}(\Omega) \cap \dot{H}^{-1,q}(\Omega)$ for $\frac{4}{3} < q < 4$, then it holds that

$$u - u^\infty \in L^{\frac{4q}{4-q}}(\Omega), \quad u^\infty \cdot \nabla u \in \dot{H}^{-1,q}(\Omega), \\ \nabla u \in L^q(\Omega), \quad p - p_\infty \in L^q(\Omega) \quad \text{for some constant } p_\infty.$$

(ii) If in addition $f \in \dot{H}^{-1,2}(\Omega) \cap L^q(\Omega)$ for $1 < q < 2$, then it holds that

$$u - u^\infty \in L^{\frac{2q}{2-q}}(\Omega), \quad \nabla u \in L^{\frac{4q}{4-q}}(\Omega) \cap L^{\frac{3q}{3-q}}(\Omega), \\ p - p_\infty \in L^{\frac{3q}{3-q}}(\Omega) \quad \text{for some constant } p_\infty, \\ \nabla^2 u, \nabla p, u^\infty \cdot \nabla u \in L^q(\Omega).$$

By taking $q = 2$ in this lemma, we have

Corollary 3.1 Every D -solution u of (N-S) with $u^\infty \neq 0$ and $f \in \dot{H}^{-1,2}(\Omega)$ satisfies

$$u - u^\infty \in L^4(\Omega), \quad u^\infty \cdot \nabla u \in \dot{H}^{-1,2}(\Omega), \quad p - p_\infty \in L^2(\Omega)$$

for some constant p_∞ .

To deal with the nonlinear term, we need

Proposition 3.1 Let $v, w \in \dot{H}_0^{1,2}(\Omega) \cap L^4(\Omega)$.

(i) If $u \in L^4(\Omega)$ with $\operatorname{div} u = 0$ in Ω , then it holds that

$$(u \cdot \nabla v, w) = -(u \cdot \nabla w, v).$$

(ii) If $u^\infty \cdot \nabla v \in \dot{H}^{-1,2}(\Omega)$ and $u^\infty \cdot \nabla w \in \dot{H}^{-1,2}(\Omega)$, then it holds that

$$\langle u^\infty \cdot \nabla v, w \rangle = -\langle u^\infty \cdot \nabla w, v \rangle, \\ \langle a \cdot \nabla v, w \rangle = -\langle a \cdot \nabla w, v \rangle \quad \text{for all } a \in A(u^\infty).$$

3.1 Proof of Theorem 1.1.

By Definition of D -solutions, we have

$$(3.1) \quad \begin{aligned} \langle f, \phi \rangle &= (\nabla u, \nabla \phi) + (u \cdot \nabla u, \phi) - (p, \operatorname{div} \phi) \\ &= (\nabla u, \nabla \phi) + ((u - a) \cdot \nabla u, \phi) + \langle a \cdot \nabla u, \phi \rangle - (p - p_\infty, \operatorname{div} \phi) \end{aligned}$$

for all $\phi \in C_0^\infty(\Omega)$. Since $C_0^\infty(\Omega)$ is dense in $\dot{H}_0^{1,2}(\Omega) \cap L^4(\Omega)$, we have

$$(3.2) \quad \langle f, \phi \rangle = (\nabla u, \nabla \phi) + ((u - a) \cdot \nabla u, \phi) + \langle a \cdot \nabla u, \phi \rangle - (p - p_\infty, \operatorname{div} \phi)$$

for all $\phi \in \dot{H}_0^{1,2}(\Omega) \cap L^4(\Omega)$. By Corollary 3.1 it holds that $u - a = u - u^\infty + u^\infty - a \in \dot{H}_0^{1,2}(\Omega) \cap L^4(\Omega)$. Hence, taking $\phi = u - a$ in (3.2), we have

$$(3.3) \quad \langle f, u - a \rangle = (\nabla u, \nabla(u - a)) + ((u - a) \cdot \nabla u, u - a) + \langle a \cdot \nabla u, u - a \rangle.$$

Furthermore by Proposition 3.1, it holds that

$$\begin{aligned} & ((u - a) \cdot \nabla u, u - a) + \langle a \cdot \nabla u, u - a \rangle \\ &= ((u - a) \cdot \nabla(u - a), u - a) + \langle a \cdot \nabla(u - a), u - a \rangle \\ & \quad + ((u - a) \cdot \nabla a, u - a) + \langle a \cdot \nabla a, u - a \rangle \\ &= (u \cdot \nabla a, u - a), \end{aligned}$$

from which and (3.3) we obtain

$$\|\nabla u\|_{L^2}^2 - (\nabla u, \nabla a) + (u \cdot \nabla a, u - a) = \langle f, u - a \rangle.$$

This proves (1.1).

Assume in addition that $f \in \dot{H}^{-1,2}(\Omega) \cap L^q(\Omega)$ for some $1 < q < 2$. By Lemma 3.1 (ii), we have

$$-\Delta u + u \cdot \nabla u + \nabla p = f \quad \text{a.e. in } \Omega.$$

Note that

$$a - u^\infty \in C_{0,\sigma}^\infty(\mathbb{R}^3), \quad a - u^\infty = 0 \quad \text{on } \partial\Omega.$$

By integration by parts, we have

$$(3.4) \quad \begin{aligned} (f, a - u^\infty) &= (-\Delta u + u \cdot \nabla u + \nabla p, a - u^\infty) \\ &= (-\operatorname{div}(T(u, p)), a - u^\infty) + (u \cdot \nabla u, a - u^\infty) \\ &= (\nabla u, \nabla a) + u^\infty \cdot \int_{\partial\Omega} T(u, p) \cdot \nu dS - (u \cdot \nabla a, u). \end{aligned}$$

Addition of (3.4) and (1.1) yields that

$$(3.5) \quad \|\nabla u\|_{L^2}^2 + u^\infty \cdot \int_{\partial\Omega} T(u, p) \cdot \nu dS - (u \cdot \nabla a, a) = \langle f, u - u^\infty \rangle.$$

Since $\operatorname{supp} \nabla a$ is compact, we see easily

$$(u \cdot \nabla a, a) = 0,$$

from which and (3.5) we obtain the desired identity (1.2). This proves Theorem 1.1.

3.2 Proof of Theorem 1.2.

Step 1. We first show that there are constants $\delta_* = \delta_*(\Omega)$ and $C_*(\Omega) > 0$ such that if

$$(3.6) \quad \|f\|_{\dot{H}^{-1,2}} + |u^\infty| \leq \delta_* |u^\infty|^{\frac{1}{2}},$$

then every D -solution u of (N-S) satisfies

$$(3.7) \quad |u^\infty|^{\frac{1}{4}} \|u - a\|_{L^4} + \|\nabla u\|_{L^2} \leq C_*(\|f\|_{\dot{H}^{-1,2}} + |u^\infty|)$$

for some $a \in A(u^\infty)$. Indeed, taking $0 < R_0 < R_1 < \infty$ and $a \in A(u^\infty)$ in such a way that

$$\Omega^c = \mathbb{R}^3 \setminus \Omega \subset B_{R_0}(0), \quad \text{supp } \nabla a \subset \{R_0 < |x| < R_1\}.$$

we have

$$(3.8) \quad \|a\|_{L^\infty} + \|\nabla a\|_{L^1 \cap L^\infty} \leq C|u^\infty| \quad \text{with } C = C(\Omega).$$

By (1.1), we see that

$$\|\nabla u\|_{L^2}^2 = \langle f, u - a \rangle + (\nabla u, \nabla a) + (u \cdot \nabla a, u - a),$$

from which and (3.8) with the aid of the Young inequality it follows that

$$\|\nabla u\|_{L^2}^2 \leq \left(\frac{1}{2} + C|u^\infty| \right) \|\nabla u\|_{L^2}^2 + C\|f\|_{\dot{H}^{-1,2}}^2 + C(|u^\infty|^2 + |u^\infty|^4).$$

Hence, under the assumption

$$(3.9) \quad |u^\infty| \leq \delta_*^{(1)} \equiv \min.\{1, \frac{1}{4C}\},$$

we have

$$\begin{aligned} \frac{1}{4} \|\nabla u\|_{L^2}^2 &\leq C\|f\|_{\dot{H}^{-1,2}}^2 + C(|u^\infty|^2 + |u^\infty|^4) \\ &\leq C(\|f\|_{\dot{H}^{-1,2}}^2 + |u^\infty|^2), \end{aligned}$$

which yields that

$$(3.10) \quad \|\nabla u\|_{L^2} \leq C(\|f\|_{\dot{H}^{-1,2}} + |u^\infty|).$$

Next, we show the bound of $\|u - a\|_{L^4}$. Define $v = u - a$, and we have by (3.8) and (3.9) that

$$(3.11) \quad v \in \dot{H}_0^{1,2}(\Omega), \quad \|\nabla v\|_{L^2} \leq C(\|f\|_{\dot{H}^{-1,2}} + |u^\infty|),$$

and that

$$\begin{cases} -\Delta v + u^\infty \cdot \nabla v + \nabla \pi = f - Q(v) & \text{in } \Omega, \\ \text{div } v = 0 & \text{in } \Omega, \\ v = 0 & \text{on } \partial\Omega, \\ v(x) \rightarrow 0 & \text{as } |x| \rightarrow \infty, \end{cases}$$

where

$$Q(v) \equiv v \cdot \nabla v + (a - u^\infty) \cdot \nabla v + v \cdot \nabla a - \Delta a + a \cdot \nabla a.$$

By (3.8) and (3.11), it holds that

$$\begin{aligned}
\|v \cdot \nabla v\|_{L^{\frac{4}{3}}} &\leq \|v\|_{L^4} \|\nabla v\|_{L^2} \leq C(\|f\|_{\dot{H}^{-1,2}} + |u^\infty|) \|v\|_{L^4} \\
\|Q(v) - v \cdot \nabla v\|_{\dot{H}^{-1,2}} &= \|(a - u^\infty) \cdot \nabla v + v \cdot \nabla a - \Delta a + a \cdot \nabla a\|_{\dot{H}^{-1,2}} \\
&\leq C(\|\nabla v\|_{L^2} + |u^\infty|) \\
&\leq C(\|f\|_{\dot{H}^{-1,2}} + |u^\infty|).
\end{aligned}$$

Hence, it follows from Lemma 2.1 and Lemma 2.2 with $q = 2$ in (i) and with $q = \frac{4}{3}$ in (ii) that

$$\begin{aligned}
\|v\|_{L^4} &\leq C \left(\frac{1}{k_1} \|f - Q(v) - v \cdot \nabla v\|_{\dot{H}^{-1,2}} + \frac{1}{k_2} \|v \cdot \nabla v\|_{L^{\frac{4}{3}}} \right) \\
(3.12) \quad &\leq C \left(\frac{1}{k_1} (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|) + \frac{1}{k_2} (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|) \|v\|_{L^4} \right).
\end{aligned}$$

Hence, under the assumption

$$(3.13) \quad \frac{1}{k_2} (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|) \leq \delta_* \equiv \min\{\delta_*^{(1)}, \frac{1}{2C}\},$$

we have

$$(3.14) \quad \|u - a\|_{L^4} = \|v\|_{L^4} \leq \frac{C}{k_1} (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|).$$

Since the assumption (3.13) necessarily implies the assumption (3.9), we see by (3.10) and (3.14) that if

$$\|f\|_{\dot{H}^{-1,2}} + |u^\infty| \leq \delta_* |u^\infty|^{\frac{1}{2}},$$

then it holds that

$$|u^\infty|^{\frac{1}{4}} \|u - a\|_{L^4} + \|\nabla u\|_{L^4} \leq (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|),$$

which implies (3.7)

Step 2. We next show uniqueness. Let u_1 and u_2 be two D -solutions of (N-S). Define $v_1 = u_1 - a$ and $v_2 = u_2 - a$ with $a \in A(u^\infty)$ as in Step1. Then $v \equiv v_1 - v_2 = u_1 - u_2$ fulfills

$$\left\{ \begin{array}{l} -\Delta v + u^\infty \cdot \nabla v + \nabla \pi = -v_1 \cdot \nabla v - v \cdot \nabla u_2 \quad \text{in } \Omega, \\ \operatorname{div} v = 0 \quad \text{in } \Omega, \\ v = 0 \quad \text{on } \partial\Omega, \\ v(x) \rightarrow 0 \quad \text{as } |x| \rightarrow \infty, \end{array} \right.$$

Hence it follows from Lemmata 2.1 and 2.1 with

$$\begin{aligned}
f &= -v_1 \cdot \nabla v = \operatorname{div}(v_1 \otimes v) \quad \text{for } q = 2 \text{ in (i),} \\
f &= -v \cdot \nabla u_2 \quad \text{for } q = \frac{4}{3} \text{ in (ii)}
\end{aligned}$$

that

$$\begin{aligned}
 \|v\|_{L^4} &\leq C \left(\frac{1}{k_1} \|\operatorname{div} (v_1 \otimes v)\|_{\dot{H}^{-1,2}} + \frac{1}{k_2} \|v \cdot \nabla u_2\|_{L^{\frac{4}{3}}} \right) \\
 &\leq C \left(\frac{1}{k_1} \|v_1 \otimes v\|_{L^2} + \frac{1}{k_2} \|v\|_{L^4} \|\nabla u_2\|_{L^2} \right) \\
 (3.15) \quad &\leq C \left(\frac{1}{k_1} \|v_1\|_{L^4} + \frac{1}{k_2} \|\nabla u_2\|_{L^2} \right) \|v\|_{L^4}.
 \end{aligned}$$

By Step1, under the assumption

$$\|f\|_{\dot{H}^{-1,2}} + |u^\infty| \leq \delta_* |u^\infty|^{\frac{1}{2}},$$

we have

$$\|v_1\|_{L^4} \leq \frac{C}{k_1} (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|), \quad \|\nabla u_2\|_{L^2} \leq C (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|),$$

from which and (3.15) with $k_1^2 = k_2$ it follows that

$$(3.16) \quad \|v\|_{L^4} \leq \frac{C}{k_2} (\|f\|_{\dot{H}^{-1,2}} + |u^\infty|) \|v\|_{L^4}.$$

Now, define $\delta_1 = \delta_1(\Omega)$ so that

$$\delta_1 \equiv \min. \left\{ \delta_*, \frac{1}{2C} \right\}.$$

Then under the assumption

$$\|f\|_{\dot{H}^{-1,2}} + |u^\infty| \leq \delta_1 |u^\infty|^{\frac{1}{2}},$$

it follows from (3.16) with the aid of the relation $k_2 = \min. \{1, |u^\infty|^{\frac{1}{2}}\}$ that

$$\|v\|_{L^4} \leq 0,$$

which yields the desired uniqueness result. This completes the proof of Theorem 1.2.

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